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## FULL PAPER

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# Records of sunspot and aurora during CE 960–1279 in the Chinese chronicle of the Sòng dynasty

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## Abstract

Records of sunspot and aurora observations in pre-telescopic historical documents can provide useful information about solar activity in the past. This is also true for extreme space weather events, as they may have been recorded as large sunspots observed by the naked eye or as low-latitude auroras. In this paper, we present the results of a comprehensive survey of records of sunspots and auroras in the *Sòngshǐ*, a Chinese formal chronicle spanning the tenth to the thirteenth century. This chronicle contains a record of continuous observations with well-formatted reports conducted as a policy of the government. A brief comparison of the frequency of observations of sunspots and auroras and the observations of radioisotopes as an indicator of the solar activity during corresponding periods is provided. This paper is the first step of our project in which we survey and compile the records of sunspots and auroras in historical documents from various locations and languages, ultimately providing it to the science community as online data.

**Keywords:** Aurora; Sunspot; Solar activity; Chinese chronicle; Historical resource

## Background

Historical solar magnetic activity is of great interest because it provides crucial information on the origin of solar magnetic fields and its variability as well as the relationship of solar activity and the climate of the Earth (Usoskin 2013). Telescopic sunspot observations have been recorded since the era of Galileo about 400 years ago. The sunspot number is considered to be the standard index of the solar activity (Clette et al. 2014), and indeed, it is known as the longest-term scientific data (Owens 2013). For the older solar activity, cosmogenic radionuclides such as <sup>14</sup>C and <sup>10</sup>Be are commonly used as the proxy (e.g., Stuiver and Braziunas 1989; Beer et al. 1980). Eddy (1980) pointed out that pre-telescopic historical records of sunspots, auroras, and total eclipses (shapes of solar corona) could be useful for the reconstruction of the past solar activity. Several authors have published the lists of astronomical events including naked-eye sunspots and auroras in the literature from Japan (Kanda 1933; Matsushita 1956; Nakazawa et al. 2004; Shiokawa et al. 2005), Korea (Lee et al. 2004), Arabic countries (Basurah 2006), Europe (Fritz 1873; Link 1962; Dell' Dall'Olmo

1979; Stothers 1979; Vaquero and Trigo 2005; Vaquero et al. 2010), Russia (Vyssotsky 1949), North America (Broughton 2002), the Tropical Atlantic Ocean (Vázquez and Vaquero 2010), and China (Schove and Ho 1959; Keimatsu 1976; Yau and Stephenson 1988; Saito and Ozawa 1992; Yau et al. 1995). A review on the historical records of solar activity is given in the monograph by Vaquero and Vázquez (2009).

In addition to the long-term changes, studies on historical solar activity have been attracting interest in the context of extremely intense solar flares and space weather events. Araki (2014) searched the historically largest geomagnetic sudden commencement (SC) using records of ground-based geomagnetic observations since 1868. The most intense geomagnetic storm on record is believed to be the so-called Carrington event in 1859 (Carrington 1859), whose estimated disturbance storm time (Dst) index is ~1760 nT (Tsurutani et al. 2003). The super-fast coronal mass ejection (CME) on July 23, 2012, is thought to have been as intense as the Carrington event, though it missed Earth (Baker et al. 2013; Russell et al. 2013). Another super-fast CME hit the Earth in August 1972 (Vaisberg and Zastenker 1976). This event yielded only moderate magnetic storm (Dst ~125 nT), presumably owing to the northward alignment of the interplanetary

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magnetic field, but it generated intense energetic particles and very rapid change in local geomagnetic fields (Tsurutani et al. 1992), causing significant damages in space and ground-based infrastructure (Lanzerotti 1992). If it were with a southward magnetic field, it could have produced very intense magnetic storm and aurora. Such intense energetic particles and magnetic storms severely damage space and ground infrastructure, resulting in a significant social and economic impact (NRC National Research Council 2008; Royal Academy of Engineering Report 2013). Historical records of such extreme events may provide us some insight about what is the maximum strength of the flares and CMEs, and how frequent such extreme events are.

Recently, Maehara et al. (2012) discovered numerous super-flares in the solar-type stars (slowly rotating G-type stars), whose total energies are estimated to be  $10^{33-35}$  erg, i.e., 10 to 1000 times more energetic than the most intense solar flares. Shibata et al. (2013) suggested that, theoretically, such super-flares may also occur on the present Sun. Interestingly, Miyake (2012, 2013) found that the atmospheric  $^{14}\text{C}$  content measured in tree rings exhibited marked increases during the Common Era (CE) 774 to 775 and during CE 993 to 994, which indicate sharp increases in cosmic ray fluxes during those periods. The origin of these intense cosmic ray events is not known, but one potential cause is the solar energetic particles (SEPs) caused by extreme solar flares. Although the strongest SEPs in the modern observational records cannot account for these events, the SEPs from super-flares may be intense enough to cause these  $^{14}\text{C}$  increments. Several studies have been published about the CE 774–775 including those by Usoskin et al. (2013), Cliver (2014), and Neuhäuser and Hambaryan (2014).

This paper is the first result of a project in which we aim to re-survey and compile the records of observations of sunspots and aurora from as many auroral sources as possible, and then provide the compilations as digital data to the scientific community. As a preliminary effort, in this paper, we present the data for the formal chronicle of the *Sòng* dynasty, *Sòngshǐ* (CE 960–1279), and we compare these results with data from cosmogenic radionuclide studies, such as the one performed by Miyake (2013).

## Methods

### Astronomical observations in the *Sòng* dynasty

In this study, we used the Chapter of Astronomy (*Tiānwénzhì*) in *Sòngshǐ*, mainly because it includes one of the richest sets of astronomical information among the chronicles of the Chinese dynasties. All the capitals in the *Sòng* era, where the observations were made, were located at latitudes between 30 and 35 N. This period (CE 960–1279) overlaps with the CE 993–994 event as well as the so-called Medieval Warm Period (MWP: 10 CE–14 CE).

Among historical records worldwide, Chinese chronicles are remarkable for their feasibility as scientific data. Keimatsu (1976) emphasizes the predominance of Chinese astronomical records because trained experts on astronomical observation made continuous observations at specified locations and took dated records of astronomical phenomena, often with detailed notes such as motions, shapes, and colors.

Thus, records in the Chinese official chronicles are regarded to be more objective than many other historical documents (Keimatsu 1976), but we should keep in mind that Chinese astronomical observations were also made for the purpose of “fortunetelling” for policy makers. For example,

(a) *On–March CE 1204 at night, red clouds (chíyún) appeared within white vapors, crossing the sky from the east to the west. After that, conflagrations occupied the country for eight days. Thus, astrologers regarded this as a symbol of fire.* (*Sòngshǐ*, Five Elements II b, p. 1413)

The reason for their consistent observations is based on Chinese culture and the politics of dynasties. Astronomical phenomena were traditionally thought to be signs from the heavens to the emperors reflecting their politics (i.e., stated at *Sòngshǐ*, Astronomical I, p. 949, translated text available in Appendix 1).

In order to deliver those heavenly messages to emperors, especially those of the *Sòng* dynasty, two observatories were constructed both in the imperial palace and near the capital city, *Kāifēng*, until the *Jīngkāng* Incident in CE 1126 (original text available in Appendices 2, 3, and 4, Yabuuchi 1967). Owing to their political importance, astronomical observations were made even during wars.

There is anecdotal evidence indicating the degree of sophistication and consistency of the astronomical observations in China during this period. During the invasion of the *Sòng* dynasty by the *Jīn* from the north, the *Jīn* captured *Kāifēng* in CE 1126. They broke all the observational instruments except for the spherical astrolabes, which were brought to *Běijīng* and adjusted by  $4^\circ$  in order to point to Polaris, as the instruments were moved from *Kāifēng* (35 N) to *Běijīng* (39 N) (the original text is available in Appendices 5 and 6).

After the fall of *Kāifēng*, the *Sòng* dynasty escaped southward via *Shāngqiū* (1128), *Yángzhōu* (CE 1128), and finally to *Línán*, the modern *Hángzhōu* (CE 1129–1279) (Mote 1999). It was in CE 1143 that the *Sòng* dynasty began reconstructing astrolabes. However, even during the period between CE 1126 and 1143 (without the use of astrolabes), we find records of both auroras and sunspots. This suggests that the *Sòng* dynasty continued observation even in such a chaotic time and without specially designed

instruments (original text available in Appendix 6). Of course, we still have to note that frequency and accuracy of these observations must have been influenced by the political climate and other unknown factors.

### Search method

The *Sòngshǐ* includes descriptions of many kinds of phenomena observed in the sky. Since we are interested in the past solar activities, we searched for descriptions that could be regarded as records of sunspots or auroras. For this purpose, we used a search engine, Scripta Sinica (2014), (<http://hanchi.ihp.sinica.edu.tw>) provided by Academia Sinica in Taiwan (<http://www.sinica.edu.tw>) that incorporates all the text data. This allowed us to automatically flag sentences that included keywords such as “black spot (*hēizǐ*)” and “red vapor (*chìqì*),” which may refer to sunspots and red auroras, respectively. Once the sentences that include the keywords were picked up, we read corresponding parts of the original text to check whether they actually refer to sunspots or auroras. We also calculated the moon phase to determine the sky conditions for each date of observation.

### Sunspot records

Sunspots are described as black spots or black vapors in the sun or in terms such as “the sun was weak and without light” (Saito and Ozawa 1992). In the *Astronomical Treatise of Sòngshǐ*, these are categorized in the subsection of unusual phenomena in the sun. Since this period was long before the invention of telescopes, the observations were presumably made by the naked eye during sunrises/sunsets or through clouds.

Sunspot records are often accompanied with information about number, shape, and size. Examples are given as follows:

- (a) *On 11 January CE 1077, in the sun were black spots (*hēizǐ*) as large as plums. They disappeared on 22.* (*Sòngshǐ*, Astronomy, p. 1087)
- (b) *On—June CE 1145, in the sun were black vapors (*hēiqì*) shifting back and forth.* (*Sòngshǐ*, Astronomy, p. 1088)

The sizes are expressed by comparison with something tangible. In the above example, it was “as large as plums.” The other expressions of size included are peach, glass, hen’s egg, and duck’s egg. Although we usually think of peaches as larger than plums, we do not know the relative and absolute size indicated by these expressions.

### Auroral records

Although the ancient Chinese did not know the physical nature of the phenomena, there are numbers of records that can be considered as the observations of auroras.

For example, Keimatsu (1969a, b) and Saito and Ozawa (1992) showed that the word “vapor” is likely to indicate auroras. Keimatsu (1976) listed all the luminous phenomena seen at night and also discussed whether they correspond to auroras or not.

Similarly to Keimatsu, we assume that the records of luminous phenomena observed at night are potentially those of auroras. Therefore, we surveyed the words that refer to luminous phenomena, such as vapor, light, and cloud. In the *Astronomical Treatise of Sòngshǐ*, these are categorized in the subsection of clouds and vapors. From the list of the potential auroral candidates, we manually removed the following two types. The first are those without dates. Most of these are found in the chapters explaining how fortunetelling is performed, which includes conversations between the emperor and servants or sages. Therefore, they are unlikely to be the direct records of the observations. The second type includes those seen during the daytime. Some of the daytime phenomena are presumably the halo around the sun.

Records of auroral candidates often include information about their color, motion, and direction; length, shape, and number of their bands; and sometimes the location of the observation when it was not made in the capital city. Examples of auroral records are given as follows:

- (a) *On 26 February CE 996 at night, in the west were eight long and short bands of pale-white vapors (*cāngbáiqì*) like comets. They gradually passed the Milky Way, entwined like patterned snakes.* (*Sòngshǐ*, Astronomy, p. 1308)
- (b) *21 August CE 1119, red clouds (*chìyún*) appear in the northeast direction running through 30 ways of white vapors (*báiqì*).* (*Sòngshǐ*, Astronomy, p. 1314)

The color is described as white, red, blue, yellow, or their mixture. The colors may be associated with what traditional Chinese called the Wǔxíng or Five Elements, in which the world consisted of five elements, namely metal, fire, wood, soil, and water, which correspond with colors of white, red, green, yellow, and black, respectively. Their motion and direction are usually given by the eight points of the compass.

Sometimes, these descriptions include information about constellations, planets, or the moon accompanying the auroras. Their lengths are given in units of “*chǐ*” or “*zhàng*.” In the *Sòng* Era, 1 *chǐ* was equal to 30.72 cm and 1 *zhàng* was 10 *chǐ* (Tonami et al. 2006). At this moment, we do not know how the lengths expressed using these units correspond to what was actually seen in the sky.

The shape and number of bands are described only in some of the recorded events. The shapes are expressed in a figurative way, such as “like serpents” or “like silk textiles.”



## Moon phase calculation

The moon phase is a trait of the sky that we can calculate accurately for historic dates. To do this, we referred to the 6000-year catalog of moon phases with Julian dates found at the NASA Eclipse website (<http://eclipse.gsfc.nasa.gov/phase/phasecat.html>). This catalog is based on an algorithm developed by Meeus (1998).

## Results and discussion

### Overall result

The lists of the candidates of sunspot and aurora are shown in Tables 1 and 2, respectively. In total, we found 38 sunspot candidates (black spot or black vapor in the Sun) and 193 auroral candidates (vapor/cloud/light during the night). The 193 auroral candidates include 75 white, 58 red, 28 blue white, and 32 others. The list is also available via our website: <http://www.kwasan.kyoto-u.ac.jp/~palaeo/>.

Figure 1 shows the annual number of records. We do not have enough records to see any signature of the 11-year solar cycle, but we can observe some long-term modulations. Overall, the period of CE 1100–1200 looks more active than the remainder. In particular, the sunspot records cluster during the periods of CE 1100–1145 and CE 1185–1205, when many auroral candidates are observed as well. There are also many auroral candidates during CE 1160–1175, but no sunspot candidate was found during this period.

### Color of aurora

The colors of the auroras are of interest because the colors have some information about the intensity of the auroral substorm and hence the solar activity. Usual auroras show green color from the forbidden line of atomic oxygen at 557.7 nm in the middle altitude (100–150 km), and red color of a forbidden line of atomic oxygen at 630.0 nm in the high altitude (>200 km). In very intense auroras, blue, violet, or pink colors in the low altitude (80–100 km) are sometimes seen that come from the molecular nitrogen lines in the blue and red parts of the spectrum. These lines are mostly excited by energetic electrons injected from the magnetosphere (Chamberlain 1961). Moreover, during large geomagnetic storms, so-called stable auroral red arcs (SAR arcs) become visible in the mid latitude (Rees and Roble 1975; Kozyra et al. 1997). All the auroral candidates presented in this paper are associated with colors. Among the 193 auroral candidates, 75 events are described as white, 58 as red, and 28 as blue white. The other 32 events include yellow, blue white, gold, etc. As mentioned above, the ancient Chinese use the five colors associated with the Wǔxíng, namely white, red, blue, yellow, and black. There is no green in Wǔxíng. Therefore, we assume that white colors in the Chinese records correspond to the green color of the aurora from the oxygen 557.7-nm line. Of course, there are always possibilities

that other phenomena such as clouds and atmospheric optics are included. Keeping this in mind and recalling that the observations are made in the latitude of 30–35°N, the fact that there are more white auroras than the red auroras in the Chinese record seems puzzling. In such low-latitude region, usually only the red auroras are seen. This is either because the usual aurora in the higher latitude is seen from the lower latitude so that only the red color in the higher altitude (>200 km) is visible above the horizon, or because the aurora is the SAR arc, in which case the pure red (without green) color may be visible even near the zenith.

The white (green) auroras in the record indicate that the usual auroral oval expanded as low as 30–35°N where the capital of the *Sòng* era was located. Here, we should also note that the geomagnetic latitude of China in the *Sòng* era could be higher than that in the present (Butler 1992). There are some modern observational records that the auroral oval expanded to such a low latitude during the extremely intense geomagnetic storms (Loomis 1860; Kimball 1960). Therefore, it is likely that the green auroras were observed in the capital of *Sòng* when the solar activity was strong. However, that there are more red auroras than white (green) auroras still remains puzzling.

### Naked-eye sunspots

During the *Sòng* era, the sunspot observations are likely to have been made by the naked eye. Therefore, only very large sunspots could have been detected. Schaefer (1991, 1993) developed a theoretical model of sunspot visibility, including naked-eye observations. The simplest limit of visibility can be expressed as  $\sim 1.22 \lambda/d$  ( $\lambda$  and  $d$  are the mean wavelength of sunlight and diameter of the optical system) (Vázquez and Vaquero 2010). Assuming a value of 1.5 mm for a diurnal observation, a value of 500 nm for the wavelength of the sunlight, and observers with standard eyesight (20/20 vision), the minimum angle of a naked-eye sunspot will be 70", and a sunspot larger than that or as large as one thousandth the area of the solar hemisphere can be regarded as naked-eye sunspots.

As a previous study (Heath 1994) suggests, the number of such large sunspots is a good proxy of the overall solar activity. Figure 2 shows the number of large (greater than one thousandth of the area of the hemisphere) sunspots, as well as the sunspot number (the Wolf number or the international sunspot number) in the most recent three-and-a-half solar cycles. This figure demonstrates that the number of naked-eye sunspots is in fact a good proxy for the sunspot number.

Indeed, the emergence of large (naked-eye) sunspots is likely to be the necessary condition for the occurrence of extremely intense solar flares. Shibata et al. (2013) presented a scaling law that relates the energy of solar (and

**Table 1** Sunspot records

Year	Month	Date	Description	Size	Counts	Place	Note
974	3		BS		2	Kāifēng	
1005	2	6	shade		2	Kāifēng	Crescent-like shape
1077	3	7	BV			Kāifēng	Until 21
1078	3	11	BS			Kāifēng	Until 29
1079	1	11	BS	Plum		Kāifēng	12 days
1079	3	20	BS	Plum		Kāifēng	
1103	7	1	WL			Kāifēng	
1104	11		BS	Jujube		Kāifēng	
1105	11	6	BS			Kāifēng	
1112	5	2	BS	Chestnut		Kāifēng	
1118	12	17	BS	Plum		Kāifēng	
1120	6	7	BS	Jujube		Kāifēng	
1122	1	10	BS	Plum		Kāifēng	
1129	3	22	BS			Línān	Until 4.14
1131	3	12	BS	Plum		Línān	4 days
1136	11	23	BS	Plum		Línān	Until 27
1137	3	11	BS	Plum		Línān	
1137	5	8	BS			Línān	Until 22
1138	3	16	BS			Línān	
1138	3	17	BS			Línān	
1138	11	26	BS			Línān	
1139	3		BS			Línān	For a month
1139	11	20	BS			Línān	
1145	7		BV			Línān	
1145	7		BS			Línān	
1185	2	10	BS	Jujube		Línān	
1185	2	15	BS			Línān	Until 27
1185	2	27	BS			Línān	
1186	5	23	BS	Jujube		Línān	
1186	5	26	BS			Línān	
1193	12	3	BS			Línān	Until 12
1200	9	21	BS	Jujube		Línān	Until 26
1201	1	9	BS			Línān	Until 29
1202	12	19	BS	Jujube		Línān	Until 31
1204	2	21	BS	Jujube		Línān	
1205	5	4	BS			Línān	
1238	12	5	BS			Línān	
1276	2	17	BS	Goose's egg		Línān	

Location of the observatories: *Kāifēng* (34.80 N, 114.30 E), *Lín'an* (30.25 N, 120.17 E)

BS black spots (*hēizi*), BV black vapor (*hēiqi*), WL the sun was weak and without light (*rì dàn wú guāng*), shade *jīng*

stellar) flares and the size of sunspots; for example, the maximum energy of a solar flare of a naked-eye sunspot can be around  $10^{35}$  erg ( $10^3$  times larger than our scientific observation record).

#### Comparison with $^{14}\text{C}$ data

Using the  $^{14}\text{C}$  content in tree rings, Miyake (2013) reported that there is a sharp increase reported in cosmic ray flux during CE 993–994. We did not find any candidates

**Table 2** Auroral records

Year	Month	Date	Color	Description	Direction	Length	Counts	Place	Notes	Moon phase
965	8	10	W	V	w	50 chī		Kaifēng		0.36
968	11	2	W	V	wn	20 chī	3	Kaifēng		0.31
979	5	9	W	V	wn			Kaifēng		0.38
979	5	19	W	V	wn			Kaifēng		0.71
986	2	22	R	V	n			Kaifēng	Until morning	0.34
986	2		R	V				Kaifēng		
987	2	10	W	V				Kaifēng		0.30
988	12		R	V	wn	Height 2 chī		Kaifēng		
996	2	26	BW	V	w		8	Kaifēng		0.17
1001	4	20	W	V	All		2	Kaifēng		0.81
1001	8	20	W	V				Kaifēng		0.97
1003	5	13	W	V	e-w			Kaifēng		0.33
1003	6	24	W	V				Kaifēng		0.73
1003	7	14	R	V				Kaifēng		0.42
1003	7	19	W	V			Some	Kaifēng		0.59
1003	8	15	W	V	ws			Kaifēng		0.50
1004	4		W-BW	V			10~	Kaifēng		
1004	6		W-BW	V			10~	Kaifēng		
1004	6	12	W	V		7 chī	Some	Kaifēng		0.74
1004	8	17	Y	V		5 zhàng		Kaifēng		0.97
1005	2	28	YW	V				Kaifēng	Near the moon	0.54
1005	3	21	W	V	n		5	Kaifēng		0.30
1005	11	5	W	V	e-w			Kaifēng		0.04
1006	4	14	R	V	n			Kaifēng		0.46
1006	4	14	W	V				Kaifēng	Near the moon	0.46
1006	5		Y	V				Kaifēng	Near the moon	
1007	4	12	W	V	e-w			Kaifēng		0.75
1007	4	13	W	V	s	2 zhàng		Kaifēng		0.79
1007	4	23	W	V	n	10 zhàng		Kaifēng		0.13
1007	5	13	W	V		3 zhàng		Kaifēng		0.82
1007	12	18	R	V	m	7 chī		Kaifēng		0.23
1008	2	10	Y	V				Kaifēng		0.03
1008	2	24	W	V	e-w		2	Kaifēng		0.48
1008	8		W	CV	wn		30~	Kaifēng		
1009	9	27	Y	V	es			Kaifēng		0.21
1011	1	25	BR	V				Kaifēng		0.64
1012	2	28	W	V	n	5 zhàng		Kaifēng		0.13
1014	6			V				Kaifēng		
1019	5	8	Y	V				Kaifēng		0.04
1026	10		R	V	w			Kaifēng	Sunset	
1028	5	16	BW	C	n-ws	Some		Kaifēng		0.66
1032	11	7	YW	V			5	Kaifēng		0.06

**Table 2** Auroral records (*Continued*)

1033	1	28	BW	V	wn		Kaifeng	0.85
1034	9	24	BYW	V		7 zhàng	Kaifeng	0.31
1041	9	1	W	V	e	10 zhàng	Kaifeng	0.10
1041	9	24	BW	C	wn		Kaifeng	0.89
1042	8	31	W	V-C	n		Kaifeng	0.46
1042	12		BW	C	s		Kaifeng	
1043	3	13	W	V	m-ws	20 zhàng	Kaifeng	1.00
1043	5	17	W	V	wn-es	2	Kaifeng	0.21
1043	9	23	W	V	n		Kaifeng	0.58
1043	10	22	W	V	m	2 zhàng	Kaifeng	0.58
1044	6		BW	V		10~	Kaifeng	
1044	10	16		V	en	2 zhàng	Kaifeng	0.77
1045	4	3	Y	V	e		Kaifeng	0.45
1048			W	V	n		Kaifeng	
1052	12	13	W	V	n	5 zhàng	Kaifeng	0.66
1065	5	24	W	V	wn-es		Kaifeng	0.57
1065	5	25	W	V	w		Kaifeng	0.60
1066	7	19	BW	C	e	1 zhàng	Kaifeng	0.82
1066	11		Y	V			Kaifeng	
1067	3	2	BW	C	s	3 zhàng	2 Kaifeng	0.53
1067	4		BW	C	ws	3 zhàng	2 Kaifeng	
1067	7	30	W	C	en	5 zhàng	Kaifeng	0.57
1068	2	17	BW	C	ws	4 zhàng	Kaifeng	0.38
1068	12		R	V	wn		Kaifeng	
1069	5	1	BW	C	es	3 zhàng	Kaifeng	0.28
1069	8	9	BW	C	en	1 zhàng	Kaifeng	0.66
1069	12		R	V	wn		Kaifeng	Every night this month
1072	7	27	W	C	s		Kaifeng	0.33
1074	4	13	BW-W	C-V	ws	2 zhàng	Kaifeng	Sunset
1074	5	3	BW	C	n	52 chí	Kaifeng	0.18
1074	5	13	BW	C	wn	3 zhàng	Kaifeng	0.51
1074	7	4	BW	C	s	3 zhàng	Kaifeng	0.27
1074	7	16	BW	C	s	2 zhàng	Kaifeng	0.67
1074	7	17	BW	C	e-s	2 zhàng	Kaifeng	0.70
1074	7	22	BW	C	ws	2 zhàng	Kaifeng	0.87
1074	8	9	BW	C	e		Kaifeng	0.47
1075	7	20	BW	C	en	4 zhàng	Kaifeng	0.17
1076	7	10	W	V	es		Kaifeng	0.23
1077	7	19	BW	C	en	3 zhàng	Kaifeng	0.91
1079	5	13	W	C	s	3 zhàng	Kaifeng	0.34
1079	5	16	BW	C	s	3 zhàng	Kaifeng	0.45
1082	5	21	BW	C	n	2 zhàng	Kaifeng	0.38
1088	7	24	R-W	V	en		Kaifeng	0.14
1088	8	12	R-W	V	en		Kaifeng	0.78



**Table 2** Auroral records (*Continued*)

1088	8	13	W	V	en		Kāifēng		0.81	
1088	9	23	R-W	V	n	Some	Kāifēng		0.20	
1099	10	15	R-W	V	n	5 chǐ	10	Kāifēng	0.97	
1101	1	31	R-W-Bk	V	en-w		4~	Kāifēng	0.02	
1103	1	8	W	V	w			Kāifēng	Sunset	0.94
1103	6	16	BW	V	es	3 zhàng		Kāifēng		0.34
1111	12	17	BW	V				Kāifēng		0.55
1115	4	26	W-Ra	C	n			Kāifēng		0.02
1117	6	29	R-W	C-V	en			Kāifēng		0.92
1119	5	11	R	V			10~	Kāifēng		0.01
1119	6	10	R	V	wn			Kāifēng		0.03
1119	7	15	R	V	n			Kāifēng		0.21
1119	8	21	R-W	C-V	n		30~	Kāifēng	Covered half sky	0.47
1120	3	28	R	C	en-wn			Kāifēng		0.79
1121	11	2	BW	V		3 zhàng		Kāifēng		0.82
1122	10	23	R	V	w			Kāifēng	Sunset	0.73
1125	5	15	R	C				Kāifēng		0.37
1126	2	4	RW	V	w			Kāifēng		0.34
1126	10	3	R	V	e			Kāifēng	Sunrise	0.53
1126	11	19	R	V	w			Kāifēng	Sunset	0.11
1126	12	21	R	V				Kāifēng		0.22
1127	1	11	W	V				Kāifēng		0.90
1127	1		W	V				Kāifēng		
1127	2	21	R	L	wn			Kāifēng		0.27
1127	4	5	W	V	ws-en			Kāifēng		0.74
1127	5		W	V	n			Kāifēng		
1127	9	20	R	V	en			Kāifēng		0.42
1127	9	22	R	V	en			Kāifēng		0.49
1127	9	27	R	V	en			Kāifēng	At dusk	0.65
1130	6		W	V	n		10~	Línān		
1130	6		R	L	en-es			Dòngtíng		
1130	6		R-W	V-C	wn		10~	Línān		
1130	6	18	R-W	C-V	n-es			Línān		0.37
1130	7	5	W	V	es			Línān		0.95
1137	1	31	R	V	en			Línān		0.29
1137	2	14	R	V	n			Línān		0.76
1137	2	20	R	V	en			Línān		0.96
1137	3	4	R	V	en			Línān		0.42
1137	10		R	V				Línān		
1137	12	29	R	V-C	s-en			Línān	From the evening	0.56
1138	10	6	R	V				Línān		0.03
1148	8	17	R	V	wn			Línān		0.06
1157	3		R	V				Línān		

**Table 2** Auroral records (*Continued*)

1157	4	30	R	V		Línān		0.66
1157	8	15	R	V	w	Línān	Sunset	0.30
1157	11	13	R	V	w	Línān	Sunset	0.32
1160	2		R	V	en	Línān		
1160	4	1	R	V	en	Línān		0.77
1160	12	18	W	V		Línān		0.65
1160	12	19	W	V	ws	Línān		0.68
1161	1	2	W	V		Línān		0.08
1161	12	21	W	V	e-w	Línān		0.12
1161	12	22	W	V		Línān		0.15
1164	1	21	W	V	ws	Línān		0.86
1164	2	22	W	V		Línān		0.95
1164	11	24	R	C	w	Línān	Sunset	0.28
1165	3	4	W	V	wn	Línān		0.71
1165	5	1	W	V	e-w	Línān		0.66
1165	5	11	W	V		Línān		0.99
1165	5	30	BW	V	wn-en	Línān		0.65
1165	6	3	W	V	n	Línān		0.77
1165	6	7	W	V		Línān		0.91
1165	9	12	R	V	m	Línān	From sunset to evening	0.18
1165	11	18	BW	CV	s	Línān		0.43
1165	12		R	C	w	Línān		
1165	12	25	W	V	e-w	Línān		0.75
1166	1		W	V	e-w	Línān		
1166	12	24	W	V		Línān		0.02
1167	1		W	V		Línān		
1170	12	3	R	V	e	Línān	Sunrise	0.81
1170	12	10	R	V	w	Línān	Sunset	0.05
1171	9	1	R	V	w	Línān	Sunset	1.00
1171	11	3	R	V	w	Línān	Sunset	0.13
1171	11	4	R	V	w	Línān	Sunset	0.16
1171	11	17	R	V	w	Línān	Sunset	0.61
1172	10	28	R	V	w	Línān	Sunset	0.33
1172	10	29	R	V	e	Línān	Sunrise	0.36
1176	9	29	R	V	w	Línān	Sunset	0.82
1176	9	30	R	V	e	Línān	Sunrise	0.85
1183	2	16	W	V	ws	Línān	From northern horizon to southern horizon	0.75
1187	12	17	R	V	w	Línān	Sunset	0.54
1187	12	18	R	V	e	Línān	Sunrise	0.57
1188	9	29	RY	V	s	Línān		0.24
1189	1	15	R	V	en	Línān	Sunrise	0.90
1192	2		R	V		Línān		
1193	12	5	R-W	V-C		Línān		0.35

**Table 2** Auroral records (Continued)

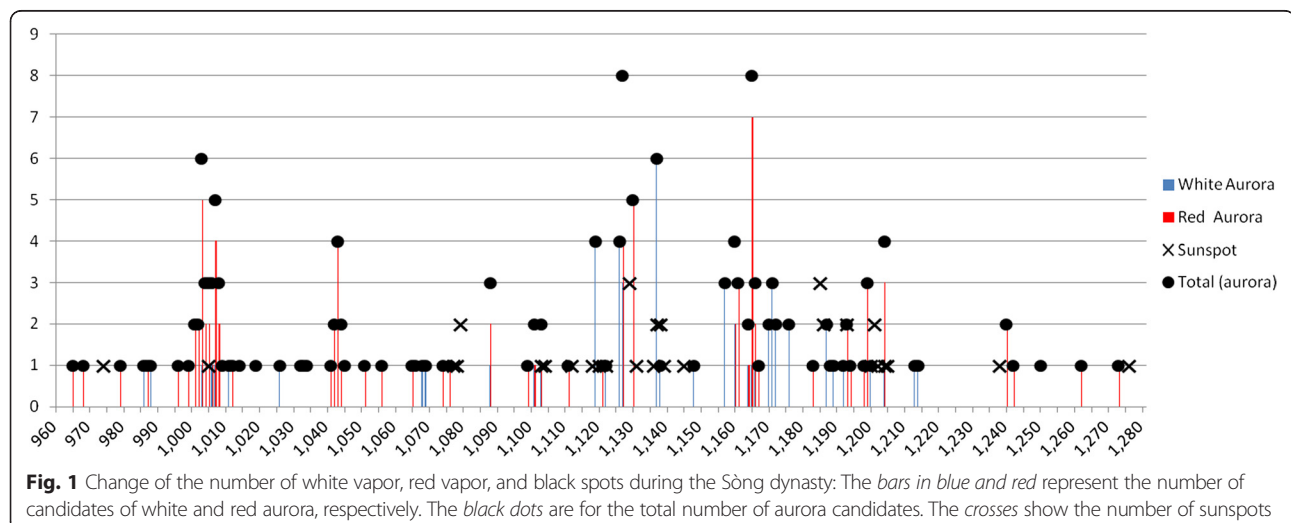
1193	12	6	R-W	V-C		Línān	0.38
1194	7	2	W	V		Línān	0.44
1194	7	9	W	V		Línān	0.68
1198	9	17	W	V		Línān	0.49
1199	3	9	W	V	en	Línān	0.42
1199	8	26	W	V	en	Línān	0.11
1199	9	7	W	V		Línān	0.51
1200	11		R	V		Línān	
1204	3	29	R	V		Línān	0.90
1204	3		R-W	C-V	en	Línān	8 days
1204	12	5	W	V		Some Línān	0.43
1204	12	16	W	V		Línān	0.79
1213	12	2	R	V	e	Línān	Sunrise 0.63
1214	1	7	R	V	w	Línān	Sunset 0.82
1240	3	16	W	V		Línān	0.73
1240	5	13	W	V		Línān	0.69
1242	3	3	W	V		Línān	0.02
1242	5	3	W	V		Línān	0.07
1250	12	10	Rb	V		Línān	0.53
1262	8	16	W	V		Línān	0.01
1273			W	V		Xiāngyáng	

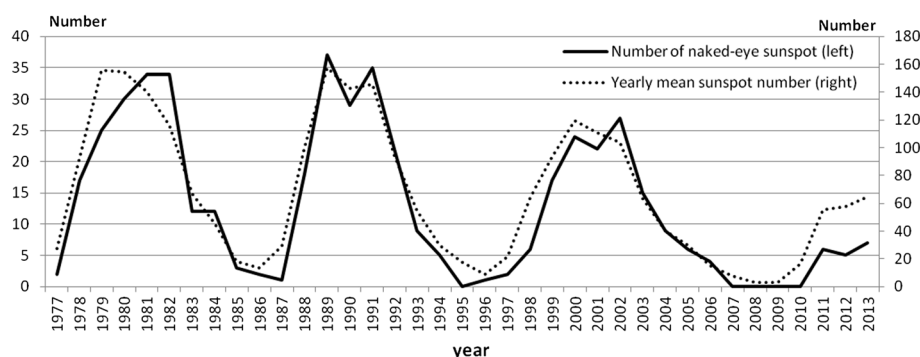
Length: *chī* (1 *chī* = 30.72 cm), *zhàng* (1 *zhàng* = 10 *chī*) (Tonami et al. 2006). Location of the observatories: *Kāifēng* (34.80 N, 114.30 E), *Línān* (30.25 N, 120.17 E), *Dòngtíng* (29.32 N, 112.95 E), *Xiāngyáng* (32.02 N, 112.16 E)

Color of auroral candidates: *W* white, *R* red, *B* blue, *Y* yellow, *Bk* black, *R-W* red and white, *RW* red white, *BW* blue white, *Ra* rainbow; types of recorded phenomena: *V* vapor (*qī*), *C* cloud (*yún*), *L* light (*guāng*); direction: *e* east, *w* west, *s* south, *n* north, *m* middle, *en* northeast; also, those abbreviations can be combined, for example *wn-es* from northwest to southeast

of sunspot nor aurora in these years. However, as can be seen in Fig. 1, we found a cluster of auroral candidates several years after this event. The closest aurora recorded is in 996 and there is a record of a sunspot in CE 1005. In this chronicle, we could not detect records clearly associated

with the CE 994 event of rapid  $^{14}\text{C}$  increase to which Miyake (2013) referred. Figure 3 shows  $^{14}\text{C}$  data from Miyake (2013) in dots with error bars and counts of *Sòngshǐ* auroral records in bars. According to Fig. 3, in CE 994, neither aurora nor sunspot observation was recorded, but





**Fig. 2** Change of the number over years for all and naked-eye sunspots: The number of naked-eye sunspots and the sunspot numbers are plotted with *solid line* and *dashed line*, respectively. The sunspot region data used for naked-eye sunspot calculation are retrieved from the NASA database (<http://solarscience.msfc.nasa.gov/greenwch.shtml>), which are originally given by the Royal Greenwich Observatory (RGO), US Air Force (USAF), and the US National Oceanic and Atmospheric Administration (NOAA). The yearly mean sunspot number is retrieved from WDC-SILSO, Royal Observatory of Belgium, Brussels (<http://www.sidc.be/silso/datafiles>)

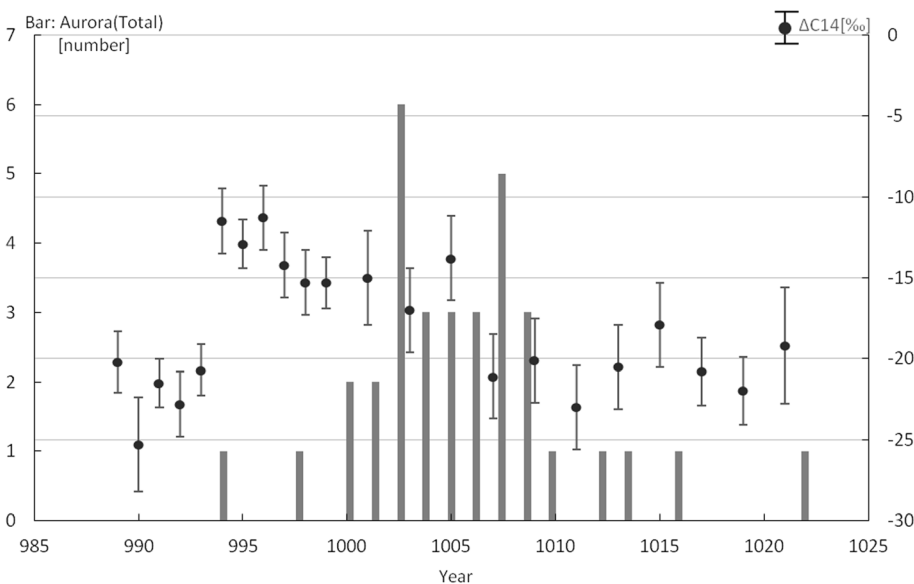
after the  $^{14}\text{C}$  peak of CE 994, the number of observed auroras increased. There are two interpretations for this. The first is that this CE 994 event is not related to a short-time solar activity such as a flare. The second is that the record that involves the CE 994 event is not recorded in the *Sòngshū* for various reasons: weather, lack of observation, lack of importance for Chinese astronomers, etc., but the increase in the solar activity during that period is reflected in the increased auroral records some years later. This kind of difficulty is one of the limitations that our surveys frequently face.

We also note that auroras around CE 993–994 were observed in other parts of the world. In Ireland, the annals

of Ulster reported a red-colored aurora observed in CE 992 (U992.4 of CELT 2000). In Korea, there is a record of a red aurora in CE 992 (Lee et al. 2004). In Germany and Denmark, three auroras in CE 992 and two auroras in CE 993 were reported (Fritz 1873). These may correspond to the astronomical event in CE 993–994.

#### Auroras and moon phase

For studies of auroral records from historical articles, concerns on moon phase might be important in estimating the actual events indicated by the records. One reason for our interest in moon phase is that there are some natural optical events possibly expressed as vapor, such as



**Fig. 3** Comparison the change of  $^{14}\text{C}$  in tree ring and the number of auroras. Miyake (2012) pointed out the spiky peak of  $^{14}\text{C}$  at CE 774 (*right*). In Chinese chronicle, after CE 774, the number of observations of auroras increased. Between CE 985 and 1025, only in CE 1005 was the observation of sunspots recorded

“moon halo” and paraselene (or “moon dog”), which occur rarely with a nearly full moon and ice crystals in cold air. This kind of atmospheric optics would occur more frequently in a polar region, but may possibly occur at lower latitudes given appropriate weather conditions. If the frequency of the “potentially aurora” records depends on the moon phase, it indicates that there may be significant number of events that are actually atmospheric optics. In order to examine this, we calculate the moon phase (0 for the previous new moon and 1 for the next new moon) and make a histogram of historical records of vapors from *Sòngshǐ*.

Figure 4 shows a histogram of the vapor records of *Sòngshǐ* where no significant tendency is found. This result may be different from the previous studies (Vaquero et al. 2003; Vaquero and Trigo 2005) of auroral observations in Europe, which mentions a marked tendency of increased auroral observation towards the last quarter of the moon phase. These previous studies conclude the possibility of this tendency due to moon illumination during the observation window from dawn to the midnight. On the other hand, the Chinese observations were made throughout the night, according to ancient Chinese articles. Therefore, no skewness of Chinese auroral records around the new moon supports the presumption of all-night observations.

## Conclusions

We have surveyed sunspot and aurora-like descriptions in the official chronicle of the *Sòng* dynasty during CE 960–1279. We found 38 sunspots and 193 auroral candidates during that period, with information of their size, color, etc. The lists are provided in this paper. This is the first step for the project in which we will survey the records of sunspot and aurora in a variety of historical documents and provide the data online for use by the

scientific community. We welcome and encourage the use of our data as well as the contributions that provide more data from diverse historical sources.

## Endnotes

<sup>1</sup>“Common Era” is a non-religious alternative of AD, namely “Anno Domini.”

<sup>2</sup>In this paper, we use the Pinyin Style to transcribe Chinese characters as the sounds of Chinese characters during the *Sòng* Dynasty are still under discussion.

## Appendices

### Appendix 1: *Sòngshǐ*, Astronomy I, p. 949

*Needless to say, the heaven is a tao. The heaven shows taos of warnings only with symbols. Therefore, from ancient times, each era had their specialists of astronomy such as ...(list of personal names)... These specialists kept observing whether the heavens were normal or abnormal. Hence, they state it as a warning of the heavens and advise it to the emperor in order to fulfill the duty of a secretary to teach his emperor not to make mistakes.*

### Appendix 2: Shenkuo, *Mengxibitan*, VIII, p. 4 (Shen 1966)

*The government put the Bureau of Astronomy (tiānwényuà) in the Imperial Court, setting clepsydras, observatories, and astrolabes equally in the Bureau of Astro-manager (sītīānjiān) and made them check each other with the Bureau of Astro-manager. Every night the Bureau of Astronomy recorded if they found unusual phenomena, clouds, or omens, and star charts on that night. They had to bring these records to the Imperial Court before the gates were opened. After the gates opened and reports were taken from the Bureau of Astro-manager, both of these reports were compared with each other and, in this way, they tried to avoid false reports.*

### Appendix 3: *Sòngshǐ*, Bureaus IV, p. 3879

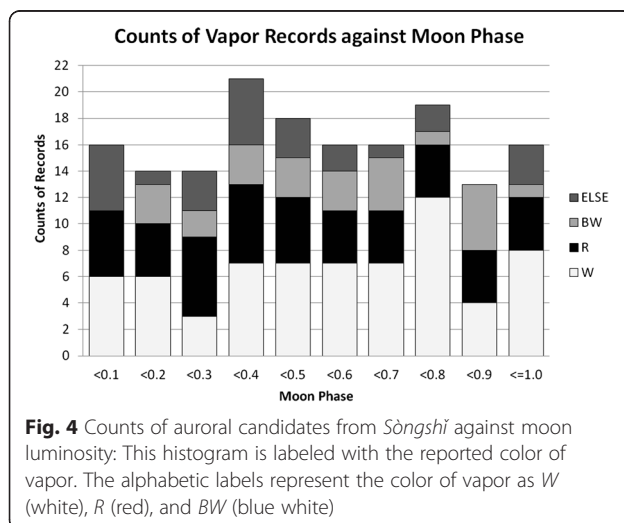
*The Bureau of Divination (tàishǐjù) is responsible for astronomical observation and designing calendars. This bureau is famous for making divinations of everything about the sun, the moon, stars, winds, clouds, weathers, and omens... On the other hand, the Bureau of Astronomy examines astrolabes and clepsydras. This bureau is responsible for observatory recordings of astronomical omens every night.*

### Appendix 4: *Sòngshǐ*, Bureaus V, p. 3923

*During the Yuánfēng years (CE 1078–85), the system of bureaus got changed. The Bureau of Astro-manager was abolished and the Bureau of Divination was established under the Ministry of Secretary.*

### Appendix 5: *Jīn shǐ*, Calendars II, p. 523

*Jīn (dynasty) had already taken Biàn (Kāifēng) and sent everything to Yàn (Běijīng). They broke all the astronomical*



*instruments such as ... (list of names of observational instruments)... except for the astrolabe. They put this astrolabe in the Bureau of Divination of the observatory. However, as it is more than thousand li from Biàn to Yàn and their altitudes are not the same, they tried to find the polar star with this instrument and succeeded by putting it 4 degree down.*

## Appendix 6: Sòngshǐ, Astronomy I, p. 950

*In the Jìngkāng Incident (CE 1126), all astronomical instruments were plundered by the Jīn people. Emperor Gāozōng escaped southward and finally in CE 1143, with a strong request of the Ministry of Secretary, he ordered the Bureau of Divination to make an astrolabe again.*

## Competing interests

The authors declare that they have no competing interests.

## Authors' contributions

This research was performed with the cooperation of authors as given: HH made philological and historical contributions. HT and ADK made contributions on the interpretation and analysis of the database. HI supervised this study. All authors read and approved the final manuscript.

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